Late Pleistocene relic Ultisols and Alfisols in an alluvial fan complex in coastal Tuscany

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Abstract: Detailed stratigraphic, sedimentary facies and palaeosol analyses were performed on an outcrop on Late Quaternary deposits in the coastal area of Tuscany. The outcrop was selected as representative of one of the major Quaternary alluvial fan complexes of Central Italy, the ancient Cecina river fan, and as showing contrasting, if related, palaeosols. The oldest relic palaeosol was identified as an Ultisol, representative of the most developed soil type normally found as relic soil in Italy, and about whose possible ages only approximate interpretations presently exist.OSL dating allowed to set the whole succession of sediments, palaeosols and geomorphic surfaces into a firm chronological setting. As a result, evolution of the Cecina fan complex in Late Pleistocene could be fully reconstructed.Assessment of the age of the relic Ultisol produced results contrasting with current interpretations, showing how such soil type can have developed in Italian conditions in a relatively short time, i.e. since about MIS 5d.

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We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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***Cover Letter**

To the Editors, Quaternary International

Object: submission of revised manuscript “Late Pleistocene, relic Ultisols and Alfisols frame an alluvial fan complex in coastal Tuscany”, by Stefano Carnicelli, Marco Benvenuti, Stefano Andreucci, Rossano Ciampalini

Dear fellows, we are now completing the submission of the revised, above manuscript, following reviewers’ comments.

Many thanks to all Editors, other Guest editors and reviewers for the effort.

Best greetings,

Stefano Carnicelli

Late Pleistocene relic Ultisols and Alfisols in an alluvial fan complex in coastal Tuscany

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Abstract

Detailed stratigraphic, sedimentary facies and palaeosol analyses were performed on an outcrop on Late Quaternary deposits in the coastal area of Tuscany. The outcrop was selected as representative of one of the major Quaternary alluvial fan complexes of Central Italy, the ancient Cecina river fan, and as showing contrasting, if related, palaeosols. The oldest relic palaeosol was identified as an Ultisol, representative of the most developed soil type normally found as relic soil in Italy, and about whose possible ages only approximate interpretations presently exist.

OSL dating set the whole succession of sediments, palaeosols and geomorphic surfaces into a firm chronological setting. As a result, evolution of the Cecina fan complex in Late Pleistocene could be fully reconstructed. Assessment of the age of the relic Ultisol produced results contrasting with current interpretations, showing how such a soil type can have developed in Italian conditions in a relatively short time, i.e. since about MIS 5d.

1 Introduction

Relic palaeosols are defined as having existed as surface, live soils for long times, going through varying environmental conditions but experiencing no or limited erosion and deposition, thus preserving the main characteristics produced by long pedogenesis. They represent unique opportunities to investigate the time required for formation of the most developed palaeosols.

Knowledge of the time required for certain palaeosols to form is of major significance for their use in stratigraphy. Firm palaeosol chronology may bridge the gap between landform stratigraphy and unconformity-based sedimentary stratigraphy, allowing correlation of landform surfaces and buried unconformities.

In many temperate to subtropical, moist areas of the world, the most developed relic soils that are commonly found are classified as Ultisols (Soil Survey Staff, 1999). This position gives Ultisols a special significance in landform stratigraphy.

Ultisols were introduced in Soil Taxonomy (Smith, 1986, p. 226) to differentiate Argillic soils occurring in, respectively, glaciated and non-glaciated parts of U.S. territory. “Non-glaciated” was intended as mostly free from glacial surface rejuvenation processes, including high-rates of aeolian deposition. A detailed study by Saif et al. (1997) revealed a fine-scale correlation between the southern boundary of loess deposition and the northern boundary of Ultisols in Ohio, USA.

Ultisols were thus conceived as having started forming earlier than Holocene and having experienced little rejuvenation, a definition very close to that of relic soils. Conversely, this definition is of little use for buried soils: base saturation (BS), the main diagnostic character for Ultisols, rarely survives burial, and is unsuitable for buried palaeosol classification (Yaalon, 1971; Krasilnikov and Calderón, 2006).

Dating of Ultisols is fairly limited in the literature. In moist subtropical climates, where they are most frequent, both numerical dating (Pai et al., 2003; Driese et al., 2007) and landform stratigraphy (Markewich and Pavich, 1991; Tsai et al, 2007) suggest Ultisols to be mostly relic soils. Two related studies based on landform stratigraphy (Bockheim et al., 1996; Lindenburg et al., 2013) support the above hypotheses and further indicate the importance of rainfall, over temperature, in determining timing and rates of Ultisol formation. In the Mediterranean, Ultisols are much less common and always considered as palaeosols. In the Guadalquivir basin of Spain (Espejo Serrano, 1985; Núñez and Recio, 2007; Saldaña et al., 2011) a consistent body of Ultisols is referred to Late Pliocene.

In Italy, Ultisols cover limited surfaces, but are not rare. The national soil data base (Costantini et al, 2013b) records 14 Soil Typological Units (STUs) as Ultisols, representing 0.25% of Italian soil cover. In Italian landform stratigraphy, Alfisols are often found on the lowest major terrace, in both river and marine sequences, and Ultisols on the next higher one. Application of both eustatic and climatic terrace development models has considered Ultisols as generically referred to MIS 7.

Filocamo et al. (2009) interpreted the second lowest marine terrace of Southern Calabria as being of MIS 7 or older age. On this terrace, Scarciglia et al. (2006) describe strongly weathered Alfisols, classified as such due to resupply of exchangeable bases from overlying recent sediments. Sauer et al. (2010) describe Ultisol-like soils on terraces along the Ionian coast of Lucania. These terraces are not dated, but are the youngest, in a well-studied terrace flight, which can be definitely said to be older than MIS 5.

Widespread evidence of Alfisols forming in Italy later than MIS 5 is available (Ajmone Marsan et al., 1988; Amorosi et al., 1996; Eppes et al., 2008; Costantini et al., 2009; Sauer et al., 2010). The absence of numerical dating, however (Carnicelli and Costantini, 2013), has prevented serious discussion of the Ultisol/MIS 7 assumption, eventually replaced by reference to "Early to Middle Pleistocene" (Napoli et al., 2006).

When moving from river or marine terraces to alluvial fan contexts, the concept of terraced surfaces acquires complexity. Palaeosol investigation may be very useful, even as a leading stratigraphic criterion (Wright and Alonso Zarza, 1990). This use requires, however, firm soil age models, backed by numerical dating.

In coastal Tuscany (Fig. 1), Alioto and Sanesi (1986) and Mori (1986) described an Ultisol on a surface interpreted as the highest in a series of eustatic marine terraces (Mazzanti and Sanesi, 1986). Boschian et al. (2006) referred this surface to Middle Pleistocene: the terrace is cut by fluvial incisions referred to Würm I (MIS 4). Alfisols develop on the formation filling such incisions, and are then interpreted as younger than MIS 4.

In the recent survey for the geological map of Tuscany, 1:10.000 scale, palaeopedological evidence was used to support stratigraphy of the Quaternary succession. Several palaeosol outcrops were examined, and a representative one was dated by Optically Stimulated Luminescence (OSL). This provided new insight into the age of the Ultisols and Alfisols of Central Italy and on the relationships between time and past climates in the genesis of highly developed palaeosols.

2 **Materials and Methods**

2.1 *Geological Setting*

The study area lies in western Tuscany, within the lower reaches of the Cecina River catchment (Fig. 1A). This watershed, of about 900 km^2, is developed on a tectono-stratigraphic pile spanning from Early Mesozoic to Quaternary. The Quaternary succession, including coastal, shallow marine and alluvial clastic deposits, was described and interpreted in lithostratigraphic terms by Mazzanti (1983) and Mazzanti and Sanesi, (1986; Fig. 2). In these studies the succession was correlated to the glacial-interglacial stages of classic Quaternary Alpine stratigraphy and on the eustatic events of Italian marine stratigraphy. This classic lithostratigraphical model was reconsidered, but substantially confirmed, by recent revisions (Boschian et al., 2006; Ciampalini et al., 2011) or discussed within an allostratigraphic approach (NASC, 1983; Sarti et al., (2007), stressing the significance of major unconformities occurring in the succession. Following surveys for the geological map of Tuscany, 1:10000 scale (http://www.regione.toscana.it/cittadini/territorio-e-paesaggio/informazione-geografica), in the present study the Quaternary succession is subdivided into two main synthems, including different sub-synthems (unconformity-bounded stratigraphic units, ISSC, 1994; Fig. 2).

Lower Pleistocene Synthem 2 is divided into sub-synthems 2B and 2A. Sub-synthem 2B encompasses three lithofacies associations: fluvial gravels and sands ($2B_1$) grade upwards and laterally into delta-front bioclastic, locally cemented, coarse-medium sands ($2B_2$); these are, in turn, locally overlain by delta-plain muds ($2B_3$). Sub-synthem 2A rests on both sub-synthem 2B and older deposits on an angular unconformity. It is made up of fluvial gravels, passing upwards to delta front-shoreface bioclastic calcareous sandstones.

Synthem 1 is represented by Middle Pleistocene to Holocene continental deposits, arranged in six sub-synthems whose upper bounding surfaces are frequently marked by palaeosols or modern soils. Sub-synthem 1F consists of alluvial, cobble- to boulder-gravels. These grade downslope to cross-stratified pebbly sands, recording a wave-dominated delta front. Sub-synthem 1E is made up of reddish sands with lenses of pebble- to cobble-gravels, which increase in frequency upstream. Sub-synthem 1D is widespread in the area, consisting of reddish, poorly sorted sands with sparse pebbles. Sub-synthem 1C is made up of red-yellowish, poorly sorted sands, and is well developed on the right side of the Cecina valley. Sub-synthems 1B and 1A represent the lowermost alluvial terraces, which mark the progressive downcutting of the valley.

The succession records a prolonged history of progradation of the Cecina river's outlet into a shallow bay (1F) first, then into the coastal plain (1E to A). The geomorphic signature of such evolution is a large, well preserved, alluvial-fan like landform (Fig. 1B), stretching eastwards about 8 km from the town of Cecina, about 20 m asl, to the highest-lying outcrops of synthem 1 deposits, at >150 m asl. This is the southern part of the original fan complex. The present-day Cecina River cut deeply into the succession, along a structural line to the north of the middle axis of the fan. Differential uplift caused much greater erosion of the northern portion, which is scarcely preserved.

Middle-Late Pleistocene units and palaeosols outcrop frequently in the area. The most interesting units for palaeosol investigation are the 1E and 1D sub-synthems. No palaeosol associated with the 1F sub-synthem was found, 1C sub-synthem is poorly represented on the right side of the Cecina river and the 1B and 1A sub-synthems carry soils of limited development. In the soil map of Toscana region (Regione Toscana, 2013), the reference soils for well preserved, well drained surfaces are, respectively:

Sub-synthem 1E: the Pianacci STU, Ultic Palexeralf

Sub-synthem 1D: the Red Riposa STU, Ultic Haploxeralf

Sub-synthem 1C: the Tripesce STU, Typic Haploxeralf

2.1.1 Reference outcrop and sampling

Out of 11 outcrops exposing palaeosols in the area, one was selected as representative of the relations between 1E and 1D sub-synthems and related palaeosols. At 43°18’59” N, 10°34’51” E, between 100 and 110 m asl (Fig. 1B), a forest road cuts across the right side of a tributary valley, about 400 m across and 20 m deep. The road cut exposes sub-synthem 1D in an inset terrace, lying some 15 m above the thalweg, and sub-synthem 1E on the shoulder portion of the interfluve surface (Fig. 3-4). Two reference sections (11A, on the terrace and 11B, on the interfluve shoulder) were described and sampled as soil profiles. Sedimentary logs were measured and described in coincidence with the soil profiles and in 4 intermediate points, to fully reconstruct stratigraphic architecture. Six samples were collected for OSL dating in coincidence with the soil profiles (Fig. 4).

2.2 Palaeosol Analysis

Description of palaeosols followed standard FAO methods (FAO, 2006). Basic analyses of palaeosol horizon samples, including pH, particle size, Cation Exchange Capacity (CEC) and Base Saturation (BS), DCB-extractable Fe (Fed) were performed according to USDA-NRCS (2004). Classification followed Soil Survey Staff (1999).

2.3 Luminescence Dating

The OSL dating method is mainly applied on quartz grains of various aeolian, fluvial, and shallow marine deposits. Although the most reliable results were obtained for coastal deposits (e.g. Madsen and Murray, 2009; Andreucci et al., 2010), many OSL applications to fluvial, alluvial and palaeosol deposits have been successful (e.g. Thiel et al., 2010, Andreucci et al., 2012, 2014). Six opaque PVC tubes (D = 8 cm; L = 40 cm) of freshly exposed alluvial and fluvial deposits (1D3, 1D4, 1M1, 1Fc1, 1E2, 1E3) were collected for OSL dating.

Optically stimulated luminescence analysis was conducted at the Sheffield Centre for International Drylands Research Luminescence Laboratory under controlled red light conditions. Material was prepared at the laboratory of the University of Sassari following the methodology described by Bateman and Catt (1996), with pure quartz in the size range 90 to 180 µm extracted for OSL analysis.

All OSL measurements were conducted on an automated Risø TL/OSL reader machine equipped with a 90Sr/90Y beta source, a blue/green LEDs used for stimulation and luminescence detection through a Hoya U-340 filter. For measurement purposes, quartz grains were mounted as a 2 mm monolayer on stainless steel disks (small aliquots).

Initial checks using infra-red stimulated luminescence were conducted to check for residual feldspar contamination: as these proved negative, a Single Aliquot Regenerative (SAR) dose protocol was used for equivalent dose, De, measurements (Murray and Wintle, 2003). The OSL measurements (80 s) were made at 125°C, after pre-heating aliquots for 10 s at 220°C and a cut heat of 160°C. The pre-heat value was derived experimentally, based on the results of a dose recovery pre-heat plateau test. Five regeneration points were measured during the SAR procedure, including a recycling point, which was used to determine the effectiveness of the sensitivity corrections. All aliquots had recycling values within 1.1 ± 0.1 and each sample showed good OSL characteristics with a strong OSL signal, dominated by a fast component which grew well with laboratory dose (Fig. 5). Up to 24 replicate palaeodoses per sample were attained, to give an indication of the reproducibility of the palaeodose measurements and to attempt to assess sample bleaching behaviour (Table 5).

The environmental dose rate (Dr) of the samples was calculated by measuring the concentration of the major radioactive elements (K, U and Th) in 10 g sub-samples (obtained by riffling); inductively coupled plasma mass spectrometry (ICP-MS) was used for U and Th and inductively coupled plasma atomic emission spectroscopy (ICP-AES) for K. ICP-MS/AES measurements were carried out at SGS laboratories, Canada, on samples completely digested using sodium peroxide fusion. Values, given in Table 5, were converted to annual Dr using pre-determined data incorporating attenuation factors (Marsh et al., 2002). The contribution to dose rates from cosmic sources was calculated using the expression published in Prescott and Hutton (1994).

To estimate a representative moisture content across sample life, this was assumed to be represented by the average between the normal minimum soil water content, as represented by the wilting point, and the water content of a fully-drained soil at field capacity, the maximum water content a soil can hold for any significant time. Higher contents were assumed as negligible in such well-drained soils. Water content at wilting point and at field capacity (-20 kPa water potential) were assessed by solving the van Genuchten equation (van Genuchten, 1980) with coefficients estimated from soil particle size distribution through the Rosetta model (Schaap et al., 2001). These are fairly standard and widely tested procedures in soil-water studies.

3. Results

3.1 Stratigraphy and Sedimentary Facies

The overall stratigraphic layout is outlined in Fig. 4. Three erosional surfaces were traced across the outcrop. The intermediate surface, representing the contact between sub-synthems 1E and 1D, shows very strong relief, with a near-vertical segment.

The lower beds (logs 1-2, Fig. 4), part of sub-synthem 1E, are partitioned by the lower erosional surface into sub-units $1E_1$ and $1E_2$. Sub-unit $1E_1$ shows crudely and horizontally bedded pebble- to cobble-sized conglomerate and sandstone layers (Fig. 3A). Conglomerates are polymodal, sub-rounded and arranged in a clast-supported framework with abundant sandy-silty matrix. Clasts are mostly made up of weathered sandstone, siltstone and diaspore with some cobbles of hard, high-Si limestone, typical of Ligurid units. In log 3, just below the steepest segment of the main erosional surface, sub-unit $1E_1$ shows fractures and filled cracks, hinting at bank collapse phenomena.

Sandstones are coarse-medium, massive or normally graded. According to sedimentological models for alluvial-fan deposition (Todd, 1989; Benvenuti and Martini, 2002), such bedding and textural features indicate grain-size bipartition. Each conglomerate-sandstone couplet records the settling of a single, sediment-laden flood-flow, expanding on the fan surface. The overlying $1E_2$ sub-unit shows a sharp variation in grain size and texture, being a well-rounded, pebble-sized, conglomerate, containing significantly less matrix than the underlying unit. Pedoturbation may have partly obliterated original sediment structure. We refer this unit to the fill of a fluvial channel incised within the older alluvial fan surface.

Sub-synthem 1D is also subdivided into two sub-units, separated by the upper erosive surface. Sub-unit $1D_1$ rests over older deposits through the higher-relief middle erosional surface. Two laterally-related facies were recognized. In logs 3-4 (Fig. 4), deposits above the erosive surface are massive matrix-supported pebbles and cobbles (Fig. 3B), arranged in crudely inclined, decimetre-thick beds, dipping to the south (i.e., towards the valley floor). The bank-collapse features clearly visible in sub-synthem 1E beds, just below this same surface, suggest that this lateral portion of $1D_1$ sub-unit is dominated by mass flows, reworking the underlying unit. To the south (i.e. towards the valley floor, Fig. 4) deposits show crudely, horizontally bedded pebbles and rare cobbles in an abundant muddy matrix (Fig. 3B). In each meter-thick bed, fine-grained matrix increases with an upward trend. These deposits are referred to sediment-laden flows, flowing in small channels; finally, the topmost sub-unit, $1D_{2,}$ is characterized by massive muddy sands.

3.2 Description of Palaeosols

Synthetic soil descriptions are reported in tables 1 and 3, and results of soil analyses in tables 2 and 4.

Soil profile 11B corresponds with stratigraphic log n° 1, in the interfluve shoulder position. In this profile, below the boundary between Bt and 2Bt1 horizons a thick (>3 m), series of reddish to red clay illuviation horizons is observed (Table 1 and Fig 3A). A relevant morphological character is the poor development of pedogenic structure, so that sedimentary facies could be observed and described in some detail. On the other hand, further than reddening and clay illuviation, evidence of strong weathering includes (Table 2): very low base saturation and low clay activity, high clay content, and a very low silt/clay ratio.

The upper horizons contain many less coarse fragments, are thoroughly pedoturbated and less developed, as indicatced by less reddish colours and higher base saturation. They do retain some relations to the underlying horizons, evidenced by comparable silt/clay ratios and clay activity. They are interpreted as the result of erosion and reworking in a slope environment, with some addition of fresh material. The underlying horizons represent a truncated palaeosol, buried 5 cm deeper than the common standard for buried soils (Soil Survey Staff, 1999).

Soil profile 11A corresponds with log n° 6, on the inset terrace tread (Fig. 3B). It is similar to 11B profile in terms of depth, reddening and clay illuviation (Table 3) but, apart from characteristics resulting from different parent materials, there are significant differences in terms of weathering degree (Table 4). The difference in base saturation is highly significant: soil 11A is firmly within the field of Ultic Alfisols. The difference in silt/clay ratio is also large, due to the high silt content of profile 11A. A related change is observed in the size distribution of sand: while sand in profile 11B is of mostly medium and fine sizes, sand in profile 11A is dominated by the very fine size class.

Soil 11A is then less developed than soil 11B, a genetic relation that fits the stratigraphic relation. There are a few irregularities. Clay activity in soil 11A is much the same as in soil 11B, both being quite low. The deepest Bt horizon in soil 11A has a base saturation definitely lower than the above-lying horizons. The simplest explanation is that soil 11A developed from materials recycled from erosion of soil 11B, with an addition of fresh material.

3.3 Luminescence Dating

A total of six OSL ages were obtained. On the basis of the data presented, the samples appear to be reproducible and to have been reset prior to burial. Thus, they should provide true burial ages.

OSL ages as well as various related data from the samples analysed are shown in Table 5 and briefly described below and in Fig. 4.

Samples 1e3 and 1e2, coming from the alluvial fan facies in $1E_1$ sub-unit, returned ages of 168 ± 8 ka and 138 ± 7 ka, respectively, dating the upper part of $1E_1$ sub-unit to MIS 6. Sample 1e1, from the overlying channel facies of $1E_2$ sub-unit, showed an OSL age of 111 ± 5 ka, implying that the fluvial phase of sub-unit $1E_2$ dates from MIS 5d. Sample 1d3, coming from sub-unit $1D_1$, showed and age of 93 ± 7 ka; the succeeding 1d2 and 1d1 samples, coming from the main body of 1D sub-synthem, returned ages of, respectively, 85 ± 4 ka and 62 ± 3 ka, illustrating aggradation of this unit from MIS 5a to MIS 4.

4.Discussion

4.1 Depositional History

The data presented allow reconstruction of a history of the development of the Cecina alluvial fan system in latest Middle to Late Pleistocene. Above the first-order erosional surface separating synthem 2 from synthem 1, the evolution from the fluvio-deltaic facies of 1F sub-synthem to the fully continental facies of sub-synthem 1E depicts a regressive succession.

The main body of sub-synthem 1E records a phase of high-energy alluvial fan aggradation; according to OSL dates of 168 ± 8 ka and 138 ± 7 ka, this phase took place under glacial conditions, during MIS 6. The date returned by sub-unit $1E_2$ implies that the end of MIS 6 and the full interglacial (MIS 5e) are represented, in the outcrop, by an erosional lag. This lag is clearly related to the establishment, across the outcrop site, of a major river, likely to have been the palaeo-Cecina, thus indicating seawards progradation of the river system. This event is recorded by sub-unit $1E_2$, which documents a phase of channel aggradation taking place during MIS 5d.

The transition between 1E and 1D sub-synthems is marked by a second-order erosional surface, frequently outcropping in the area, as reviewed by Boschian et al. (2006). With its characteristic topography, this surface outlines here the right bank of an entrenched box valley (Carnicelli et al., 2009), recording the start of the development of a valley which, through successive cut-and-fill cycles, developed into the present-day one. In this outcrop, sub-synthem 1D records the first, major, valley fill cycle; evolution of facies from $1D_1$ to $1D_2$ sub-units testifies the progressive decrease of aggradation rates typical of such valley fill successions, the massive muddy sands of $1D_2$ marking the valley overfilling phase (Benvenuti et al., 2005). Several, similar low-order valleys are incised into the ancient alluvial fan surface.

The development of such valleys, and the changes in sediment facies, indicate a major river avulsion, taking place at some time between MIS 5d and MIS 5b. Most likely, this episode represented the beginning of the deep entrenchment of the Cecina River into the older fan and of the evolution of the present-day hydrography. This kind of changes appears to be a response to a rapid base level lowering, caused by relative sea level dropping (Fig. 6).

The valley fill represented by 1D sub-synthem was deposited between the end of MIS 5 (5a) and full MIS 4. As dating does not reach the top of the unit, the age of the succeeding incision cycle is undetermined.

4.2 Landforms and Palaeosols Development

In the time interval exposed by the outcrop, development of two well distinct landform surfaces can be reconstructed and constrained within Late Pleistocene chronology. The interfluve surface, the depositional top of 1E sub-synthem, became an abandoned and terraced alluvial fan after the main river avulsion. The valley side terrace is a morphological expression of the 1D sub-synthem. The geological map and previous studies indicate that this inset valley terrace is the proximal extension of a broader surface, lying downslope and representing a progradation stage of the alluvial fan complex.

The palaeosols formed on the two surfaces are clearly observable, and their genesis can be interpreted in the context of stratigraphic, geomorphic and chronological relations.

The soil on the older surface, profile 11B, is a shallow-buried palaeosol. The characters of the buried horizon sequence suggest that it represents the deep portion of a thick, strongly developed soil, i.e., the portion formed below the zones of high biological activity and disturbance from wetting/drying cycles. The pedogenic properties of the different preserved horizons are fully consistent, and there is no evidence of any serious disturbance. The sequence can then be interpreted as the result of a single soil formation history. The erosional surface separating $1E_1$ and $1E_2$ sub-units is older than the soil formation episode we observe. Any soil development that might have taken place on top of sub-unit $1E_1$, i.e. in full Eemian conditions, was not preserved in this outcrop.

Nevertheless, this palaeosol clearly records a major soil formation episode: it is clear that it attained a high degree of weathering as a deep, fully developed, Ultisol. Though it was not possible to confirm that this was exactly the same soil described in Alioto and Sanesi (1986), it represents the same soil type (the Pianacci STU) and soil-stratigraphic unit. Available data clearly imply that this soil formed starting after 111 ± 5 ka, i.e. later than the MIS 5e climate optimum. Present climate conditions (Costantini et al, 2013a) allow for only about 100 mm excess water available in winter for leaching. It is thus highly likely that this time span has seen long periods with a higher water excess, likely during transitions to glacial and interstadial times. Overall, these data support the hypothesis that rainfall budget and time are much more important in Ultisol development than was temperature (Bockheim et al, 1996; Lindenburg et al., 2013).

The soil formed on the valley terrace, an Ultic Alfisol, is significantly less developed. Evidence suggests it to have formed from a mixture of materials reworked from the older surface with a significant addition of fresh materials, causing reversal of such weathering indicators as BS and silt/clay ratio; particle size data (Table 4) suggest an aeolian contribution. Map-wise, the 1D sub-synthem generally corresponds with the Val di Gori sands formation (Fig. 2), within which evidence of aeolian contributions was noted by Mazzanti and Sanesi (1986).

The genetic and chronological relationship between the two palaeosols is entirely consistent with both stratigraphic and landform relationships. The development of the ancient Cecina alluvial fan followed the fully entrenched model (Wright and Alonso Zarza, 1990, Fig. 6). Consistency between different stratigraphic criteria allowed high accuracy mapping of Late Quaternary units in the area (see supplementary material).

5. Conclusions

The combined analysis of sedimentary successions, geomorphic surfaces and soils allowed detailed reconstruction of the evolution of a large, old alluvial fan complex.

The soils presented in this study supply significant new insight about the age of the most developed relic palaeosols to be found frequently in Italy, about which knowledge is presently limited. While the age of the Alfisol on the 1D sub-synthem is consistent with relatively widespread numerical dating of Alfisols of Italy, the age of the Ultisol on the interfluve surface is in clear contrast with currently accepted concepts. The possibility of such soil type developing after the MIS 5e climatic optimum has never been seriously considered in Italian, and Mediterranean, literature. It appears then that soil development proceeded, during the Late Pleistocene of Italy, at faster rates than usually thought, possibly influenced by moister rainfall regimes. A general inference of palaeopedological meaning to be drawn from this new dating evidence is that highly developed soils may be more the product of long-term geomorphic stability than of specific climate optima.

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Captions

Figure 1: geological and geomorphological setting; A) location map and schematic geology of Cecina river catchment; B) Prospect view, looking to north-east, of the lower reaches of Cecina river valley and coastal plain; the main preserved part of the Cecina fan complex is on the right, with outcrop location marked by star; from Google Earth

Figure 2: Chronostratigraphic schemes of the Quaternary succession in the Cecina coastal area, comparing previous reconstructions with the subdivisions adopted in this study.

Figure 3: The studied outcrop; A): from log 1 to log 2, notebook in white circle for scale; B) from log 3 to log 6, hammer in white circle for scale

Figure 4: Stratigraphy of the studied outcrop, with position of logs, soil profiles and dated samples, and dating results.

Figure 5: a) Quartz OSL SAR-growth curve for sample 1e3 based on eight regenerative doses (small black circle). The diagram also shows the natural signal = white circle. Note that despite the high De value, the sample is below the 85% of 2Do. A typical regenerative decay curve for quartz sample 1e3 shown inset. b) Quartz OSL SAR-growth curve for sample 1d1 based on eight regenerative doses (small black circle). Note that despite the high dose rate value (2.79 ± 0.1 Gy/ka), sample 1d1 is below the 85% of 2Do.

Figure 6: Conceptual sketches of the evolution of the Cecina fan complex, based on the studied outcrop (rectangle). A): the Cecina fan during deposition of $1E_1$ sub-unit; B): river incision and fan progradation, as indicated by $1E_2$ sub-unit; C): further river incision and progradation, with formation of a tributary drainage of box-shaped valleys, during deposition of 1D sub-synthem.

Figure

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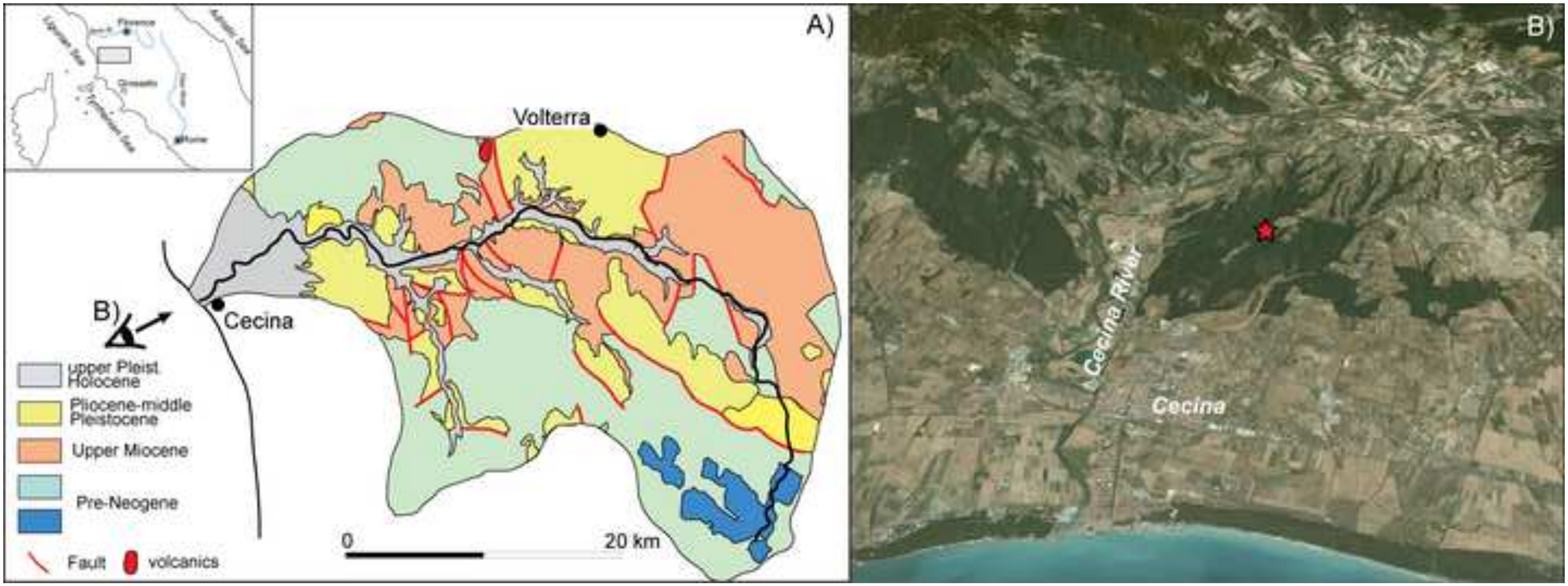

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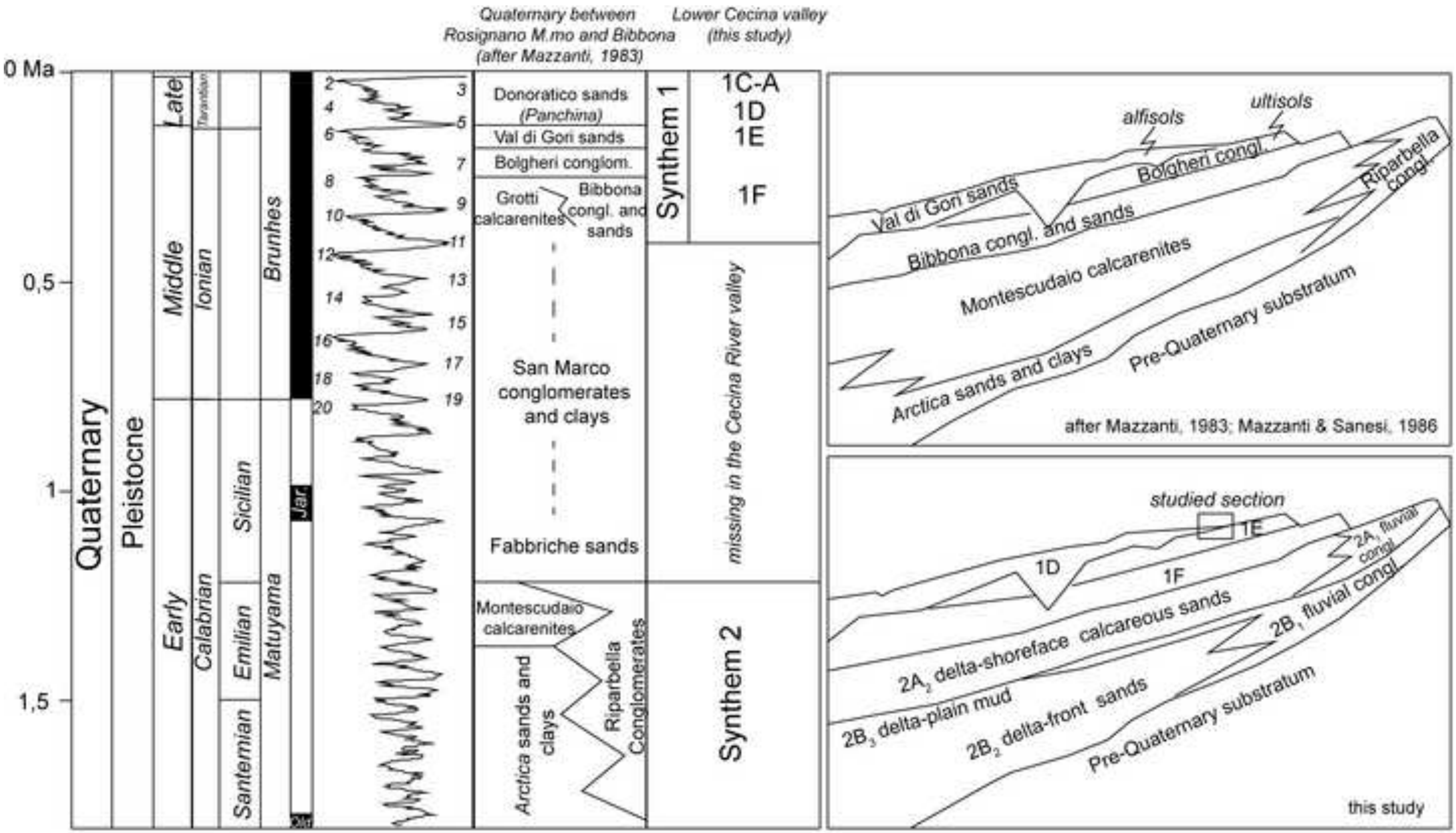

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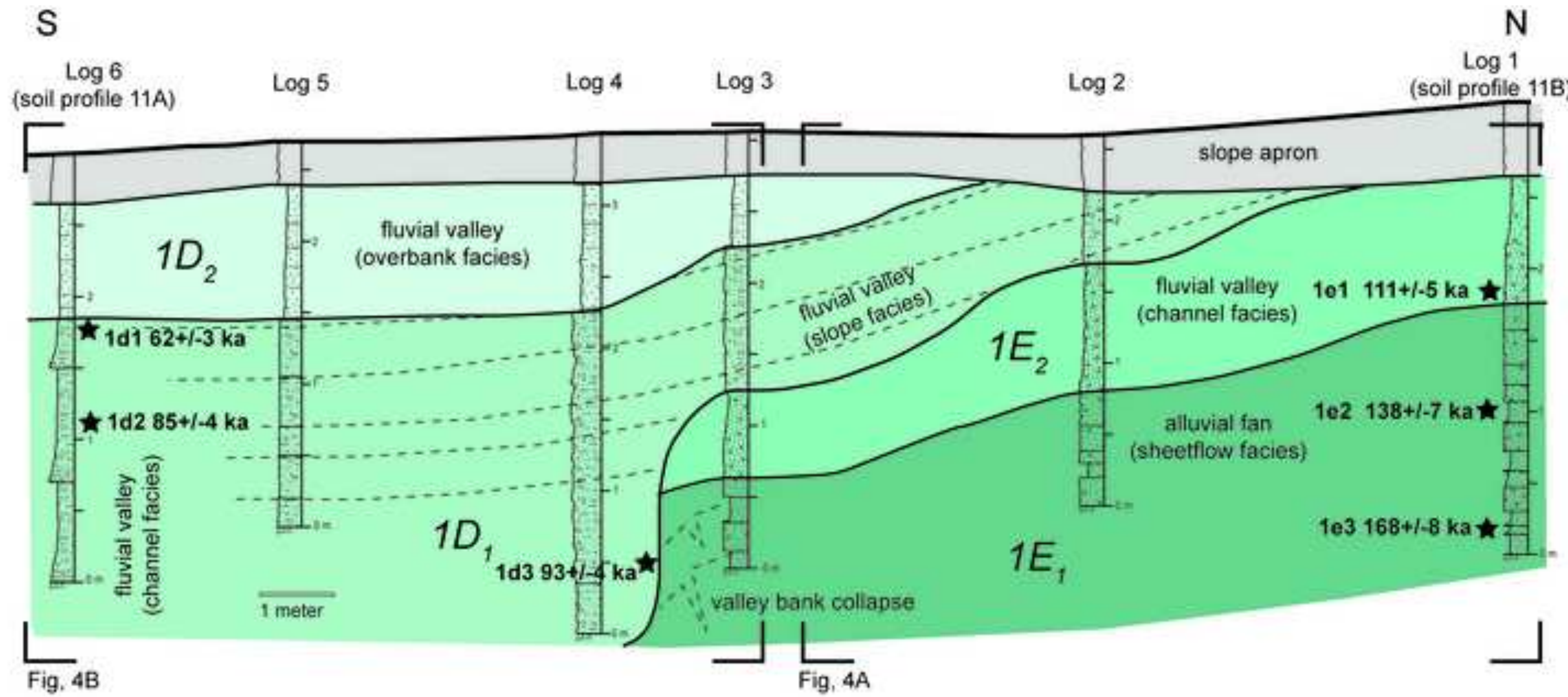

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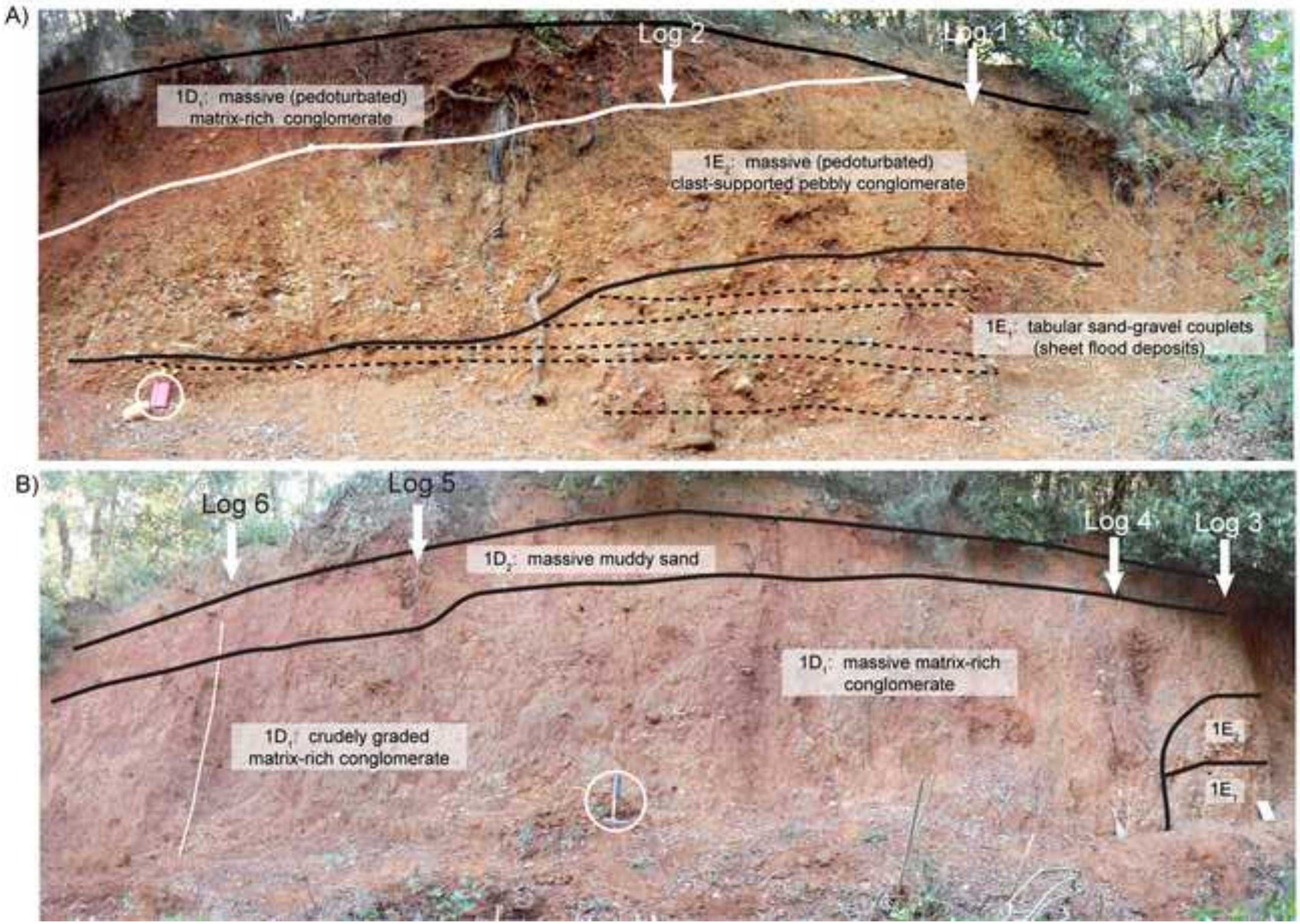

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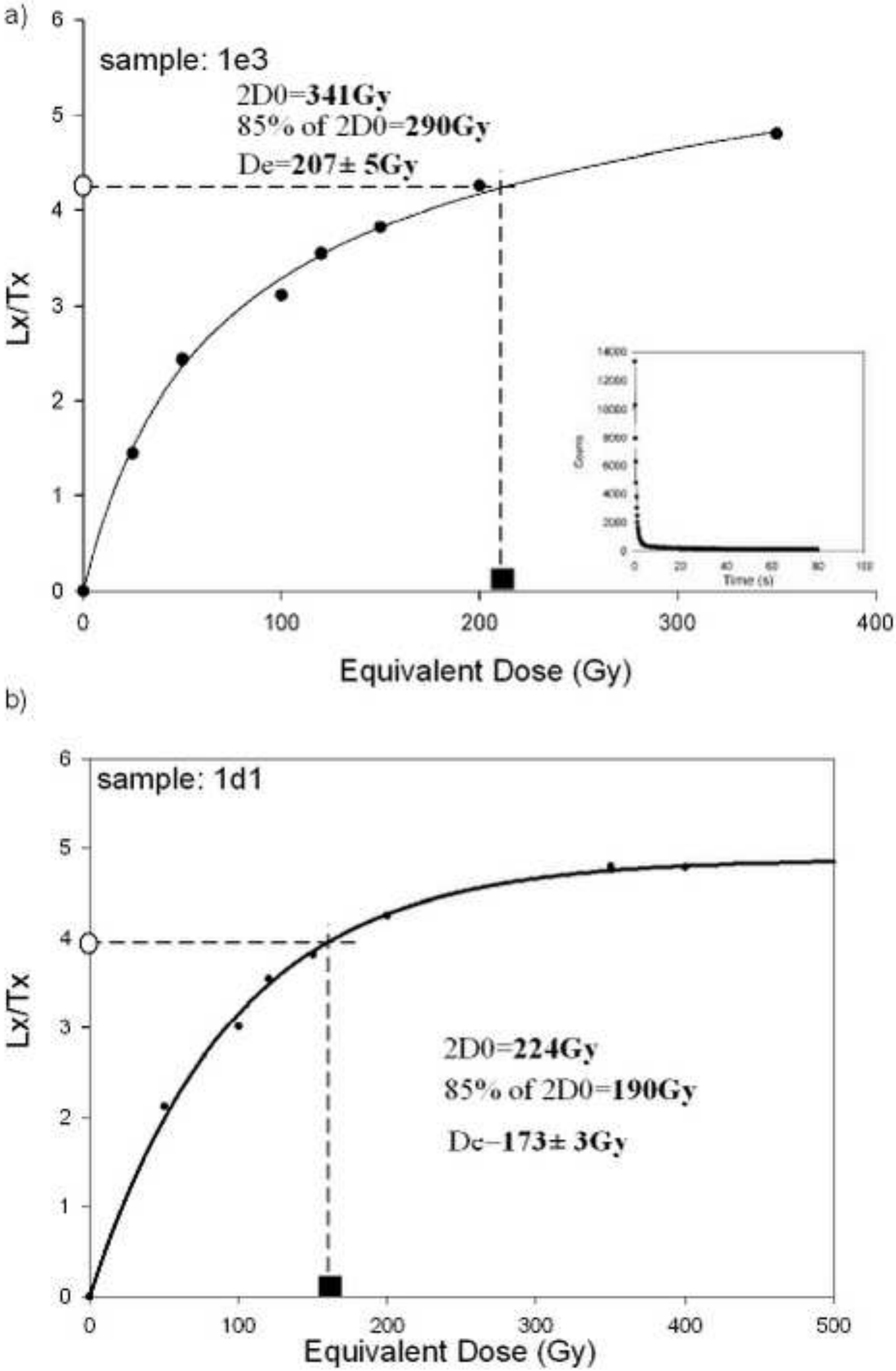

Figure 6 (former 7)
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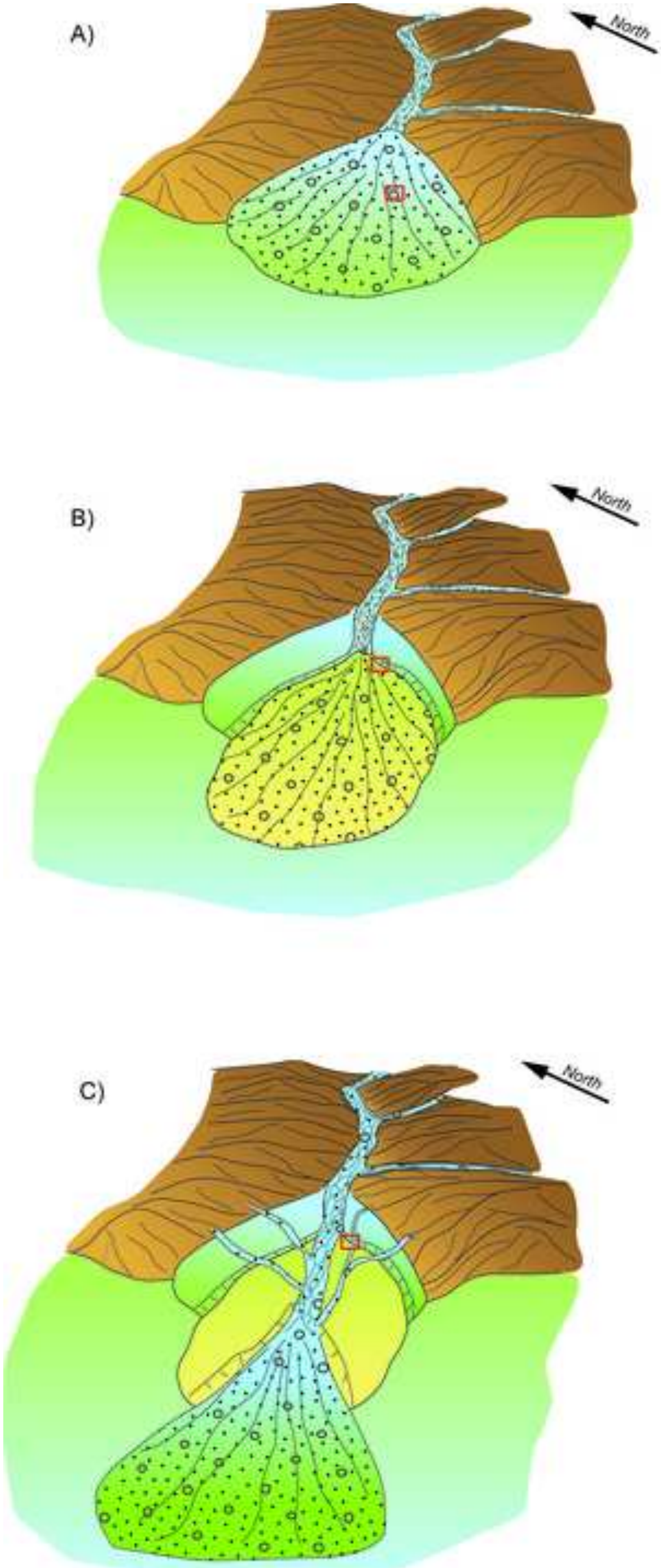

Supplementary figure 1

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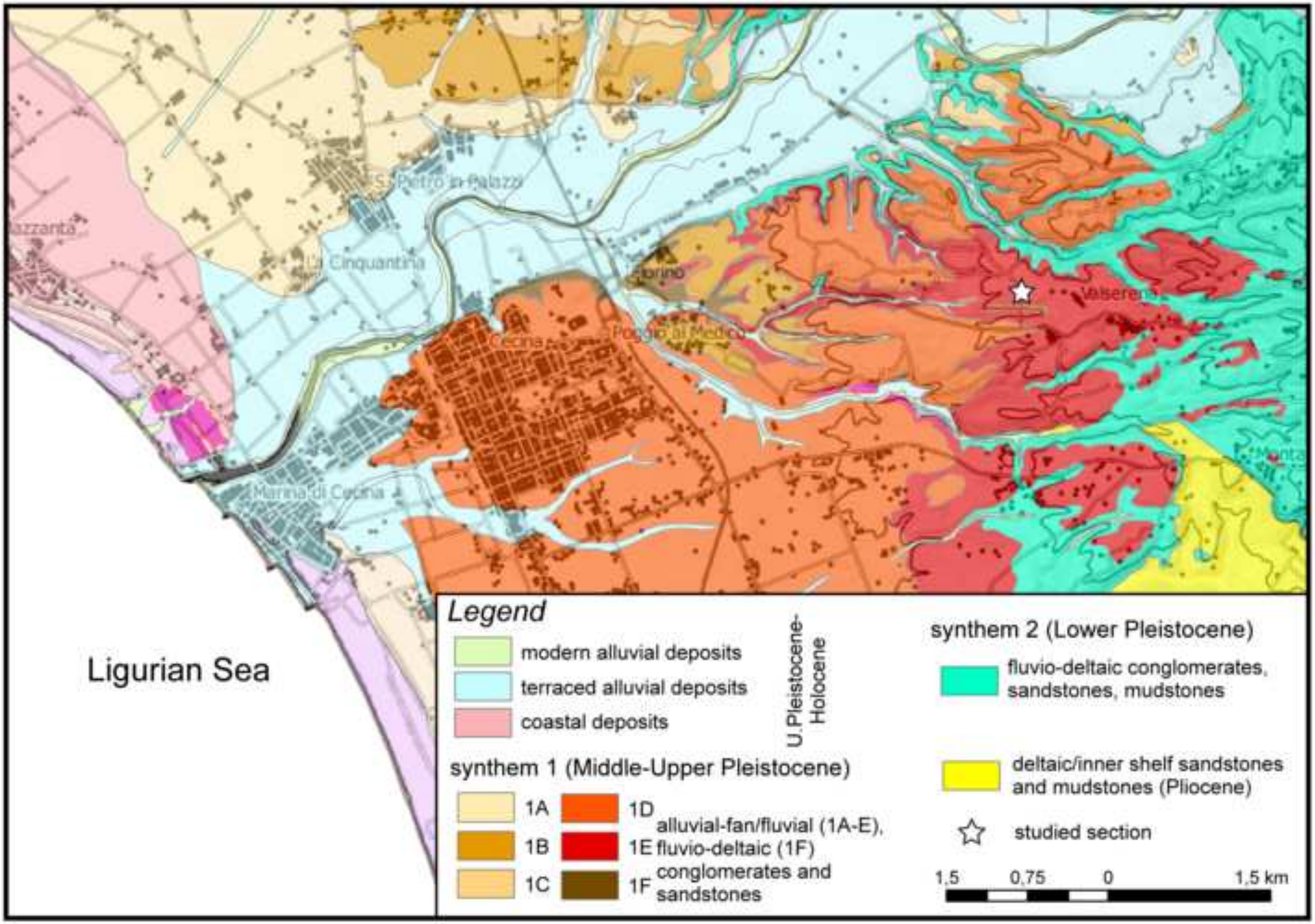

Caption to supplementary figure 1

Supplementary material figure 1

Schematic geological map of the lower reaches of the Cecina river, showing the main Late Quaternary units and the location of the studied outcrop.

Table

TABLE 1: description and stratigraphy of soil profile SPC 11b

Stratigraphic unit		Soil	Horizon	Depth	Field description
STRATIGRPHIC UNIT	SLOPE	II	AE	0-15	Fine, moderate, blocky subangular structure; moist, 7.5YR 6/6; 10% fine subrounded gravel; segregated organic granular peds; clear wavy boundary
			EB	15-35	Medium, moderate, blocky subangular structure; moist, 7.5YR 4/6; 5% fine rounded gravel; gradual, wavy boundary
			Bt	35-55	Coarse, moderate, blocky subangular structure; moist, 7.5YR 4/4; 10% fine rounded gravel; discontinuous, 7.5YR 5/6 clay coatings on peds and coarse fragments; clear, wavy boundary
	$1E_2$	I	2Bt1b	55-100	Structureless, friable; moist, 7.5YR 4/6; bleached tongues, 0.5-2 cm wide, 10 YR 7/4; 40% very fine, rounded gravel; continuous, 2.5YR 4/6 clay coatings on pores and coarse fragments; clear smooth boundary
			2Bt2b	100-145	Structureless, friable; moist, 5YR 4/6; bleached tongues continuous from overlying horizon; 40% very fine, rounded gravel; continuous, 2.5YR 4/6 clay coatings on pores and coarse fragments; clear smooth boundary
	$1E_1$		3Bt3b	145-210	Structureless, friable; alternating decimetre-sized beds, either 20% very fine, rounded, gravel or 40% medium, rounded, weathered gravel; dry, crushed, 5YR 4/4 fine earth; discontinuous, iron-rich clay coatings, in clusters; clear, smooth boundary
			3C1b	210-230	Single sand bed; moist 5YR 4/6; discontinuous clay coatings on sand grains; few iron manganese nodules; clear wavy boundary
			3C2b	230-300	Structureless, friable; alternating decimetre-sized beds, either 40% medium, rounded, gravel or 40% unsorted, rounded, fragments up to 10 cm; dry, crushed, 5YR 4/4; clay coatings on fragments; iron manganese nodules

Table

TABLE 2: analytical data for soil profile SPC 11b

STRATIGRPHIC UNIT	Soil	Horizon	Sand, %[a] vc	c	m	f	vf	total	Silt	Clay	pH_w	CEC[b]	Fe_d	Si/C	Activity	BS[c]
									%			$cmolc^+ \cdot kg^{-1}$	$g \cdot kg^{-1}$	Ratio		%
SLOPE	II	AE	8.5	6.9	10.0	14.2	10.9	50.5	41.5	8.0				5.2		
SLOPE	II	EB	12.5	7.1	11.8	18.0	7.4	56.8	32.8	10.4				3.2		
SLOPE	II	Bt	14.7	11.5	9.6	10.5	3.4	49.8	16.6	33.6	5.2	15.1	9.2	0.5	0.45	43.9
MUP3a	I	2Bt1b	18.4	11.8	9.2	7.6	2.1	49.1	14.7	36.2	4.9	20.1	16.6	0.4	0.55	32.0
MUP3a	I	2Bt2b	3.4	3.0	7.5	27.2	5.1	46.2	16.6	37.2	4.7	20.1	13.4	0.4	0.54	28.2
MUP2	I	3Bt3b	11.0	9.1	12.3	19.3	3.8	55.6	19.4	25.1	4.8	18.6	11.0	0.8	0.74	32.2
MUP2	I	3C1b	0.1	4.9	49.9	20.5	0.8	76.3	7.8	15.9	4.7	15.9	5.6	0.5	1.00	40.6
MUP2	I	3C2b	11.7	13.2	25.8	18.0	2.1	70.7	11.0	18.2	5.1	13.0	7.6	0.6	0.71	48.9

[a]vc: >1000 µm; c: 500-1000 µm; m: 250-500 µm; f: 125-250 µm; vf: 53-125 µm
[b]: by NH_4-COOH, pH 7
[c]: by sum of bases

Table

TABLE 3: description and stratigraphy of soil profile SPC 11a

STRATIGRPHIC UNIT	Soil	Horizon	Depth	Field description
SLOPE	II	A1	0-9	Medium, moderate, blocky subangular structure; moist, 7.5YR 3/3; 15% fine, fresh, rounded gravel; clear wavy boundary
		A2	9-17	Medium, moderate, blocky subangular structure; moist, 7.5YR 3/4; 5% fine, fresh, rounded gravel; clear wavy boundary
		2EB	17-35	Medium, moderate, blocky subangular structure; moist, 5YR 4/4; few, fine gravel; bleached sand grains; clear smooth boundary
$1D_2$		2Bt1	35-50	Medium, moderate, blocky subangular structure; moist, 5YR 4/6; few fine gravel; discontinuous, iron-rich, clay coatings on peds and coarse fragments; abrupt, smooth boundary
		2Bt2	50-125	Fine, moderate, prismatic structure; moist, 5YR 3/4; 5% medium, rounded gravel; discontinuous, iron-rich, clay coatings on pores and coarse fragments; common iron-manganese masses; gradual irregular boundary
$1D_1$	I	3Bt3	125-160	Fine, moderate, prismatic structure; moist, 5YR 3/3; 5% fine, rounded gravel; common bleached tongues, up to 1 cm wide, 7.5YR 5/6; continuous, iron-rich, clay coatings on pores and coarse fragments; common iron-manganese masses; gradual irregular boundary
		3Btb	160-240	Structureless, friable; moist, 5YR 3/4; 20% fine, rounded gravel; clay coatings discontinuous on grains, continuous on coarse fragments; discontinuous iron-manganese coatings on coarse fragments; common iron-manganese masses; bleached tongues continuous from overlying horizon

Table

TABLE 4: analytical data for soil profile SPC 11a

Stratigraphic unit	Soil	Horizon	Sand, %[a]						Silt	Clay	pH_w	CEC[b]	Fe_d	Si/C	Activity	BS[c]
			vc	c	m	f	vf	total	%			$cmolc^+ \cdot kg^{-1}$	$g \cdot kg^{-1}$	Ratio		%
SLOPE	II	A1	14.0	10.4	10.7	13.9	12.2	61.3	36.0	2.7				3.3		
SLOPE	II	A2	8.1	6.7	8.8	13.4	11.5	48.5	44.3	7.2				1.8		
MUP3c	II	2EB	5.6	5.1	7.5	12.5	10.8	41.5	45.0	13.5	6.1	8.4	13.4	1.3	0.62	39.4
MUP3c	II	2Bt1	3.1	3.2	5.2	9.5	9.3	30.4	44.5	25.1	6.1	14.4	15.9	1.7	0.57	30.3
MUP3c	II	2Bt2	3.9	3.2	5.6	9.6	9.6	31.9	38.7	29.4	6.4	9.9	17.4	1.7	0.34	58.0
MUP3b	I	3Bt3	4.9	4.7	7.2	12.4	12.4	41.6	36.9	21.5	6.1	9.1	13.6	3.3	0.42	52.3
MUP3b	I	3Btb	6.7	7.7	10.2	13.0	9.1	46.7	33.4	19.9	5.7	12.4	12.2	1.8	0.62	38.1

STRATIGRPHIC UNIT

[a]vc: >1000 µm; c: 500-1000 µm; m: 250-500 µm; f: 125-250 µm; vf: 53-125 µm
[b]: by NH_4-COOH, pH 7
[c]: by sum of bases

Table 5

TABLE 5 Summary of dosimetry, dose equivalent (De) measurements and luminescence ages.

Sample n.	Depth[1] (cm)	^{238}U (PPM)	^{230}Th (PPM)	K (%)	Water[2] (%)	Dr[3] (Gy/ka^{-1})	De (Gy)	*N* [4]	Age[5] (ka)
Log 6 of figure 5									
1d1	120	2.83 ±0.4[1]	10.7 ±0.4	1.6	13.4	2.79 ± 0.1	173 ± 3	22	**62 ± 3**
1d2	180	2.61 ±0.6	8.3 ±0.2	1.1	13.1	2.16 ± 0.09	184 ± 4	24	**85 ± 4**
1d3	220	2.05±0.2	8.3 ±0.3	0.6	13.1	1.5 ± 0.04	140 ± 2	24	**93 ± 4**
Log 1 of figure 5									
1e1	120	1.26±0.2	6.2 ±0.2	1.1	11.2	1.79 ± 0.05	199 ± 4	22	**111 ± 5**
1e2	220	1.05±0.2	6.0 ±0.2	0.6	11.5	1.18 ± 0.03	163 ± 5	24	**138 ± 7**
1e3	300	1.24±0.2	4.4 ±0.1	0.6	11.5	1.23 ± 0.03	207 ± 5	24	**168 ± 8**

[1] Samples position below the top of the Log
[2] selected water content value for the age calculation (see text for further details)
[3] conversion factors from activity concentrations to dose rate, from Olley et al., 1996
[4] the number of individual aliquots contributing to De
[5] uncertainties are estimated standard errors

***Detailed Response to Reviewers**

To the Editors, Quaternary International

Object: submission of revised manuscript “Late Pleistocene, relic Ultisols and Alfisols frame an alluvial fan complex in coastal Tuscany”, by Stefano Carnicelli, Marco Benvenuti, Stefano Andreucci, Rossano Ciampalini, detailed list of changes

Dear fellows, with respect to the comments sent to us, we accomplished the following modifications:

- We enlarged discussion to account for present climate conditions and their implications
- We deleted former figure 6, put dating results in former figure 3, that we renumbered figure 4, and renumbered former figure 4 as figure 3; as a consequence, former figure 7 is now figure 6.

Concerning other suggestions from reviewers, we agreed with Guest Editor not to act on them as:

- Detail analysis of possible errors in dating is too speculative, and anyway the most likely bias would be to obtain a date older than the actual one
- Considerations about carbonate content of original parent material, though highly relevant, cannot but be excessively speculative

Many thanks to all Editors, other Guest editors and reviewers for the effort.

Best greetings,

Stefano Carnicelli